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Accelerator and Beam Physics Program at IOTA/FAST: Status and Plans

Vladimir Shiltsev

DOE/OHEP briefing

December 17, 2015

Content

1) High Level Rationale & Scope for IOTA/FAST

- P5, HEPAP/GARD Subpanel, Goals, Milestones

2) 2015 IOTA/FAST – impressive achievements

- Construction/commissioning progress/timeline/issues

3) 2016 IOTA/FAST – key R&D beam facility

- Plans, issues

4) 2017 & beyond, R&D, Collaborations, etc

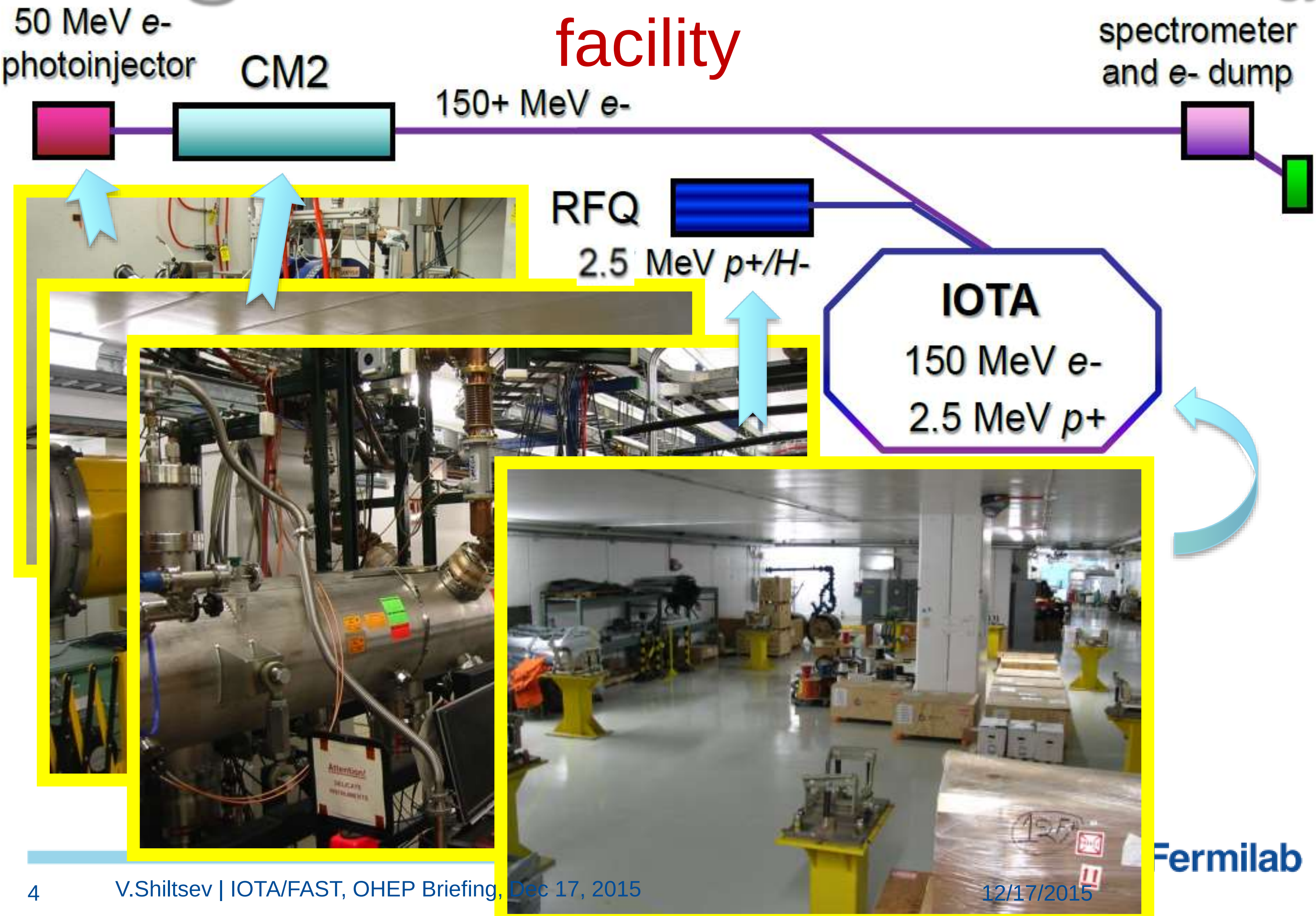
- IOTA Science Workshop April 28-29, 2015

IOTA/FAST in the GARD Program

- **Recommendation 2.** Construct the IOTA ring, and conduct experimental studies of high-current beam dynamics in integrable non-linear focusing systems. (p. 9, 18)
  - GARD thrust: Accelerator and Beam Physics
- **Recommendation 3.** Support a collaborative framework among laboratories and universities that assures sufficient support in beam simulations and *in beam instrumentation* to address beam and particle stability including strong space charge forces. (p. 9, 17)
  - GARD thrust: Accelerator and Beam Physics

	Intensity Frontier Accelerators	Hadron Colliders	e^+e^- Colliders
Current Efforts	PIP	LHC	
	PIP-II	HL-LHC	ILC
Next Steps	Multi-MW proton beam	Very high-energy *pp* collider	1 TeV class energy upgrade of ILC*
Further Future Goals	Neutrino factory*	Higher-energy upgrade	Multi-TeV collider*

IOTA @ Fermilab Accelerator Science and Technology facility



IOTA/FAST Plan

• contingent on funding
(see below)

Phase 1: FY15 -19 *

1. **Construction** of main elements of the FAST/IOTA facility:
    a) electron injector based on existing FAST electron linac
    b) IOTA ring
    c) proton injector based on existing HINS proton source
    d) special equipment for IOTA experiments.
2. **Commissioning** of the IOTA ring with 150 MeV/c electron beam – FY17/18 *
    a) need electrons to be able to measure beam optics to <1 %
3. **Research** single-particle dynamics in integrable optics with pencil electron beams – FY18/19 *
    a) need pencil e- beam to quantify phase-space dynamics

IOTA/FAST Plan

- contingent on funding

(see below)

Phase 2: FY20* - ca FY24

1. **Commission** IOTA operation with 70 MeV/c proton beams
2. **Research** space-charge compensation with nonlinear optics and electron lenses.
   a) Study the application of space-charge compensation techniques to next generation high intensity machines.
3. **Expand the program** beyond these high priority goals to allow Fermilab scientists and a broader accelerator HEP community to utilize unique proton and electron beam capabilities of the FAST/IOTA facility

FAST Program Organization

S.Nagaitsev, CAO

V.Shiltsev, APC
FAST Program Director

Construction and Commissioning

J.Leibfritz, MS
Construction
Installation, Engin'ng
Facility Operations

A.Valishev, APC
IOTA Construction
Commissioning
Beam Operations

E.Harms
SRF Installation
SRF Commissioning

D.Broemmelsiek
Beam Commissioning
Beam Operations

E.Prebys, APC
RFQ Re-Commiss'ing
RFQ Relocation

Beam Physics Research

A.Valishev, APC
Intensity Frontier Exps
Space-Charge Collab'n

S.Chattopadhyay,NIU
Advanced Physics Exp's
University Collaborations
International Collaborations

A.Valishev, APC
Integrable Optics
experiments (e-/p+)

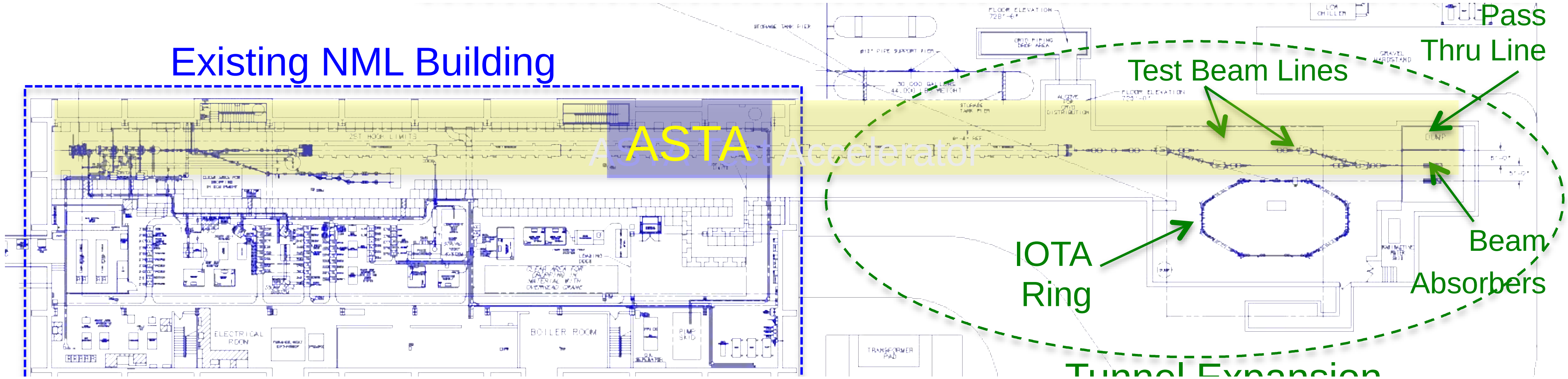
G.Stancari, APC
e-lens program, Space
-Charge Compensation

Opt.Stoch.Cooling
(V.Lebedev, et. al)
Single e- Correl.
(Swapan C., et. al)
Channeling X-ray
(P.Piot, et. al)
other experiments

Resources for FAST/IOTA at FNAL

- FAST/IOTA is a significant and recognized effort at Fermilab – one of the Director's "Top 10 Fermilab Priorities"
- Quite complex now:
  - Construction, installation, commissioning, research
- FAST/IOTA Department in Accelerator Division / Accelerator Physics Center – led by Dr. Alexander Valishev
  - Department of 15 (scientists, engineering physicists, engineers, technicians)
  - Mission: IOTA/FAST construction, operation, and research
  - Other involvements (fractions on LCLS-II/CMTS, PXIE, LARP, LDRD)
  - 3 graduate students
- Support of AD service departments
  - Mechanical Support, Electrical Eng. support, Controls, Cryo, ESH, etc
- Support of TD (Magnets department)

Fermilab Accelerator Science and Technology facility (FAST)



- ***Construction:***
  - DOE/OHEP proposal (2014): est. 18.7M$ over 2015-2017 — *start R&D*, *e- 2017*, *p+2018*
  - Funded by GARD, no extra $$, limited and flat support
    - **FY16** 9.6FTEs+726k$M&S=2,060k$ direct, or about 3.5M$ fully loaded
  - significant schedule slip w.r.t. "original optimistic plan" (ca Q1 2014)

IOTA/FAST Research Start vs $$

Timeline with $$ "as is"

FY15	**20 MeV e- commissioned** **HE beam line 30%** **IOTA parts 50%**
FY16	50 MeV e- commissioned HE beam line 100% IOTA parts 80%
FY17	150 MeV CM2 to dump IOTA installed
FY18	IOTA *e-* commissioned IOTA research starts with *e-*
FY19	Proton RFQ move 50%
FY20	Proton RFQ move 100% Proton RFQ commissioned IOTA research starts with *p+*

with extra $1.5M in FY16-18

FY15	**20 MeV e- commissioned** **HE beam line 30%** **IOTA parts 50%**
FY16	50 MeV e- commissioned HE beam line 100% IOTA parts 80%
FY17	150 MeV CM2 to dump IOTA *e-* commissioned IOTA research starts with *e-*
FY18	Proton RFQ moved 100% *p+* RFQ commissioned
FY19	IOTA research starts with *p+*
FY20	(IOTA research continues)

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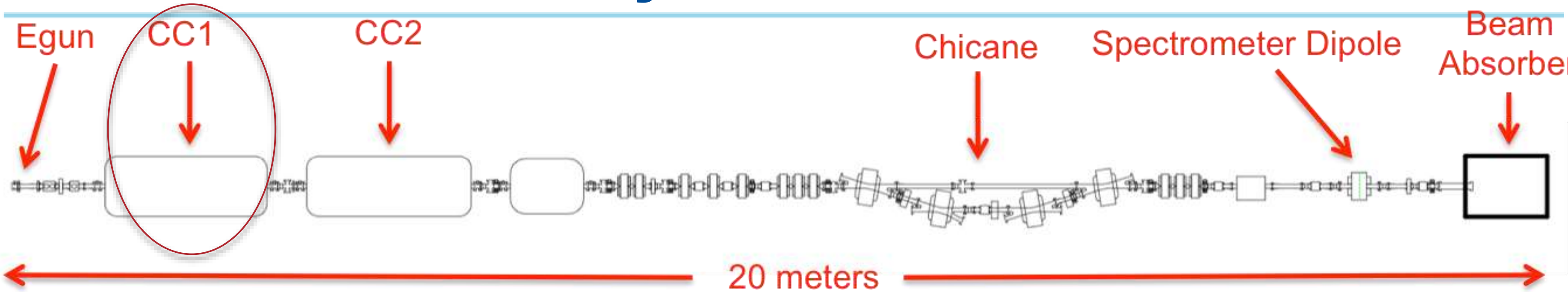
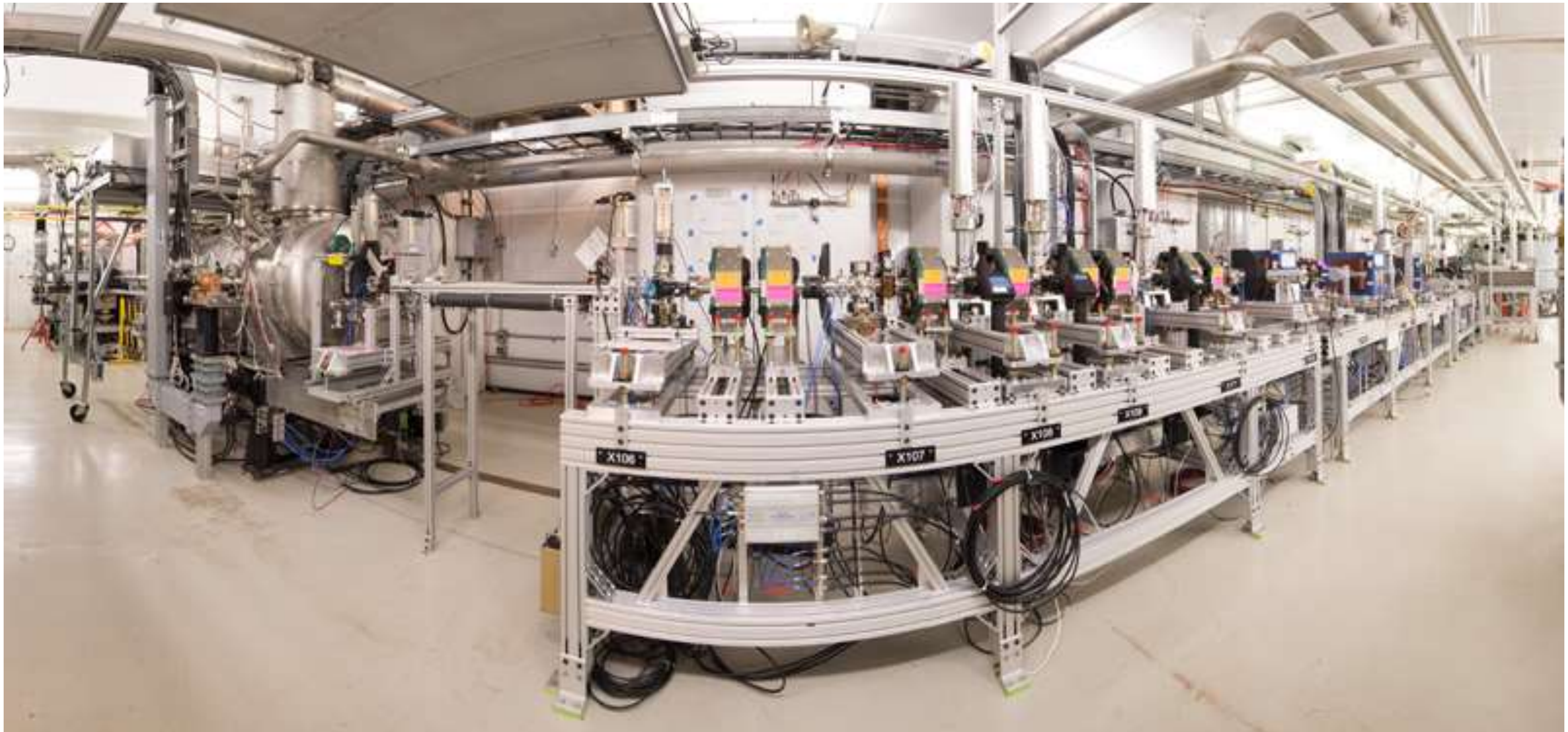
(2) FAST /IOTA in 2015

FY15	20 MeV e- commissioned HE beam line 30% IOTA parts 50%

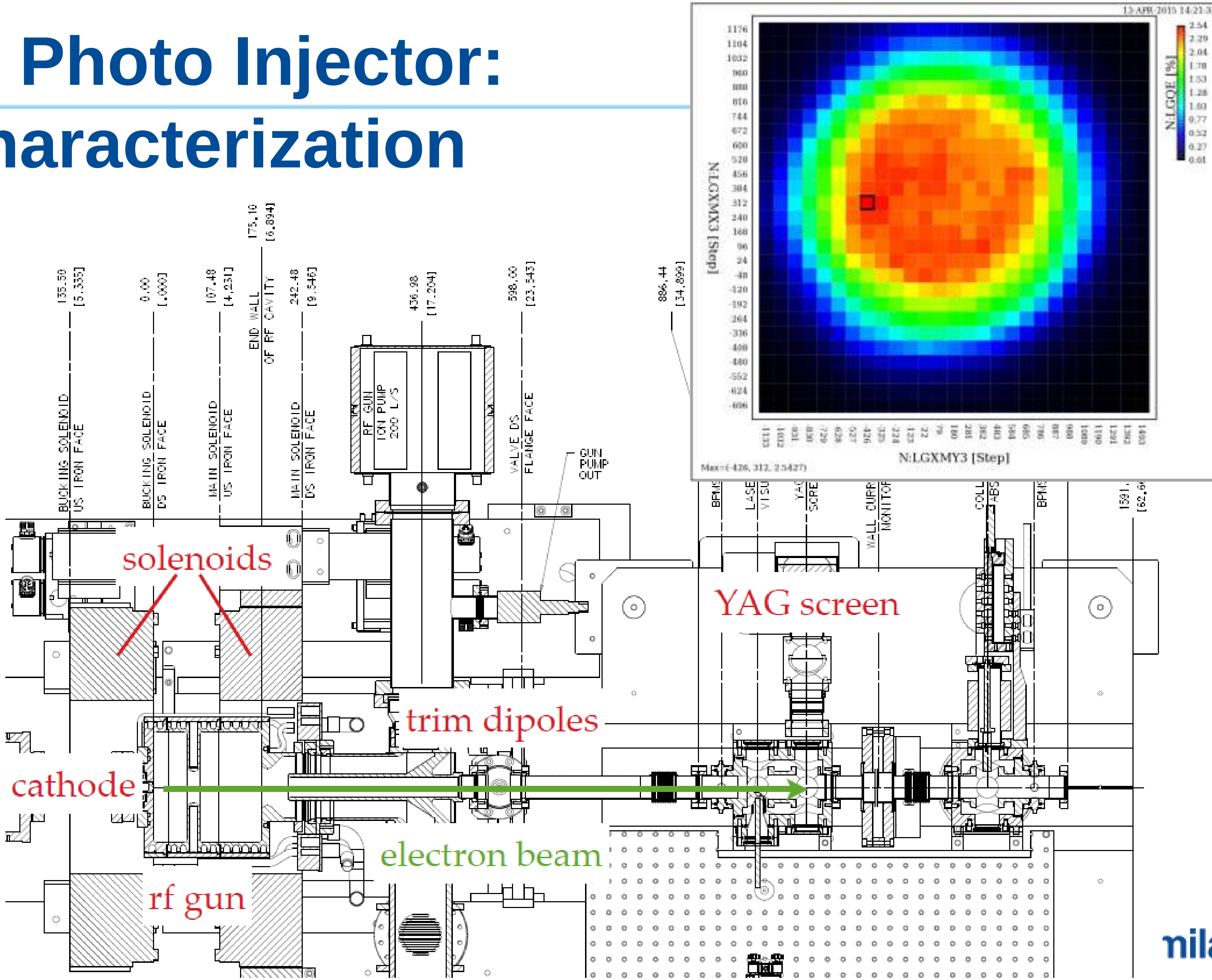
IOTA Electron Injector @ FAST





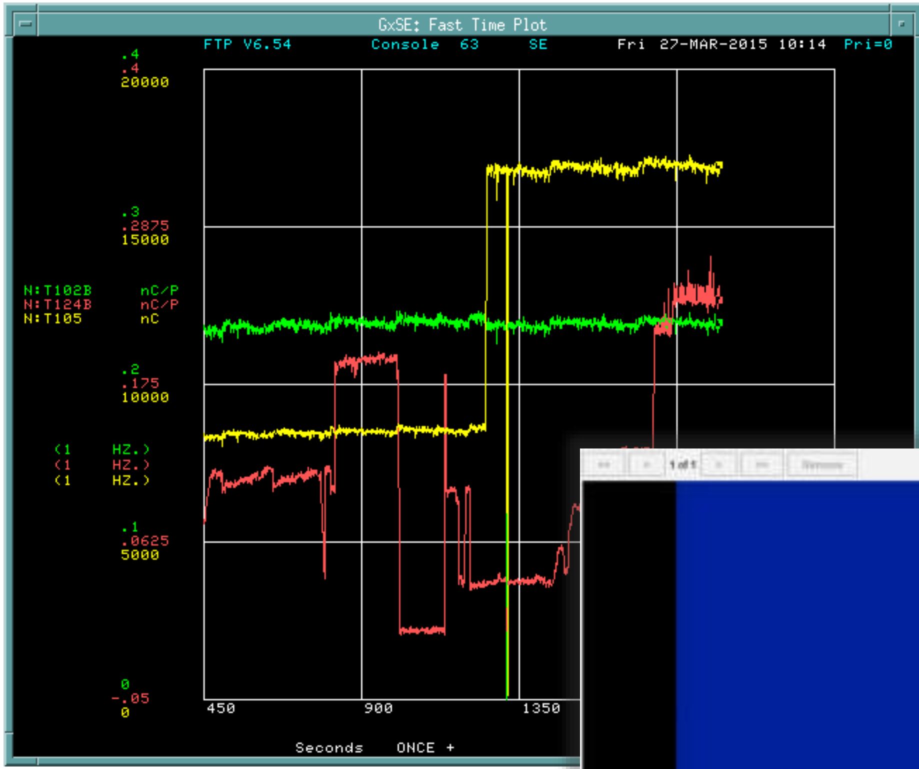
20MeV e^- beam through FAST injector

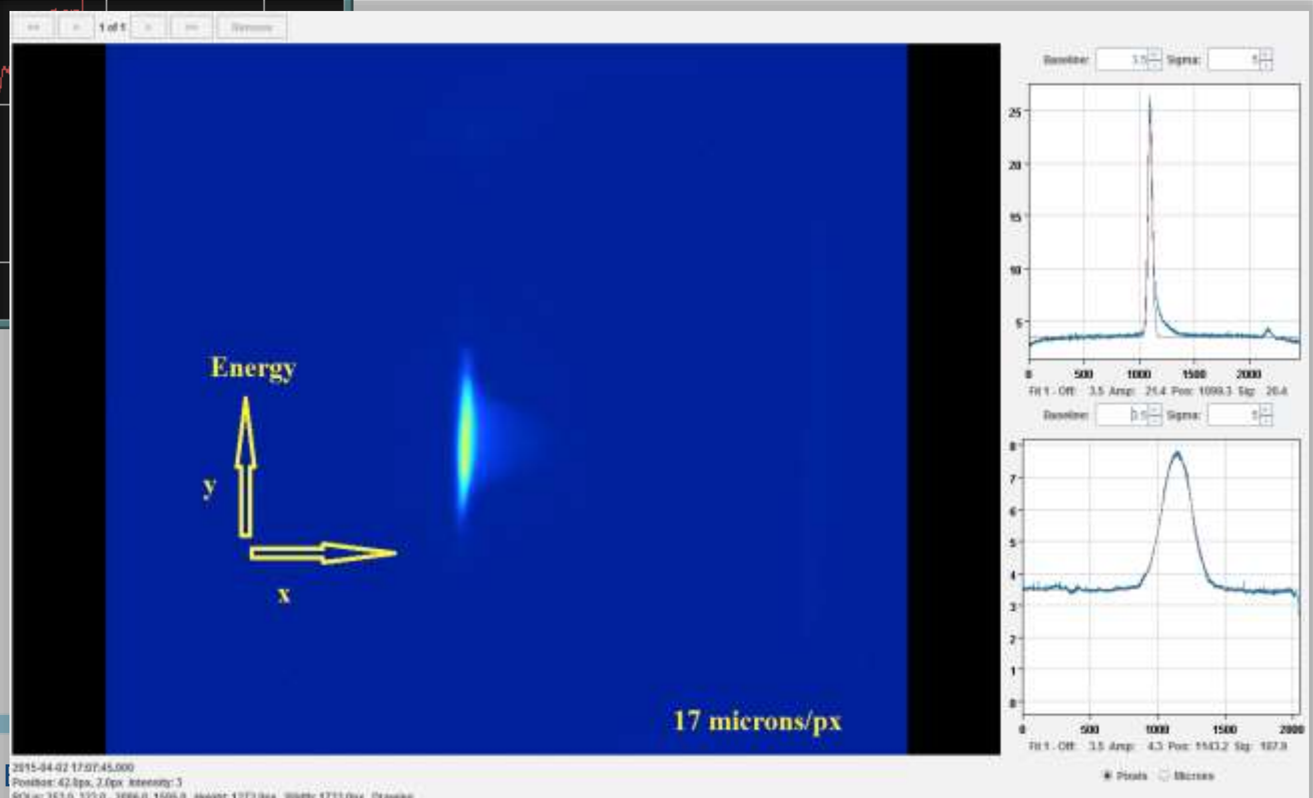
e- Photo Injector: characterization



Cathode QE Scan

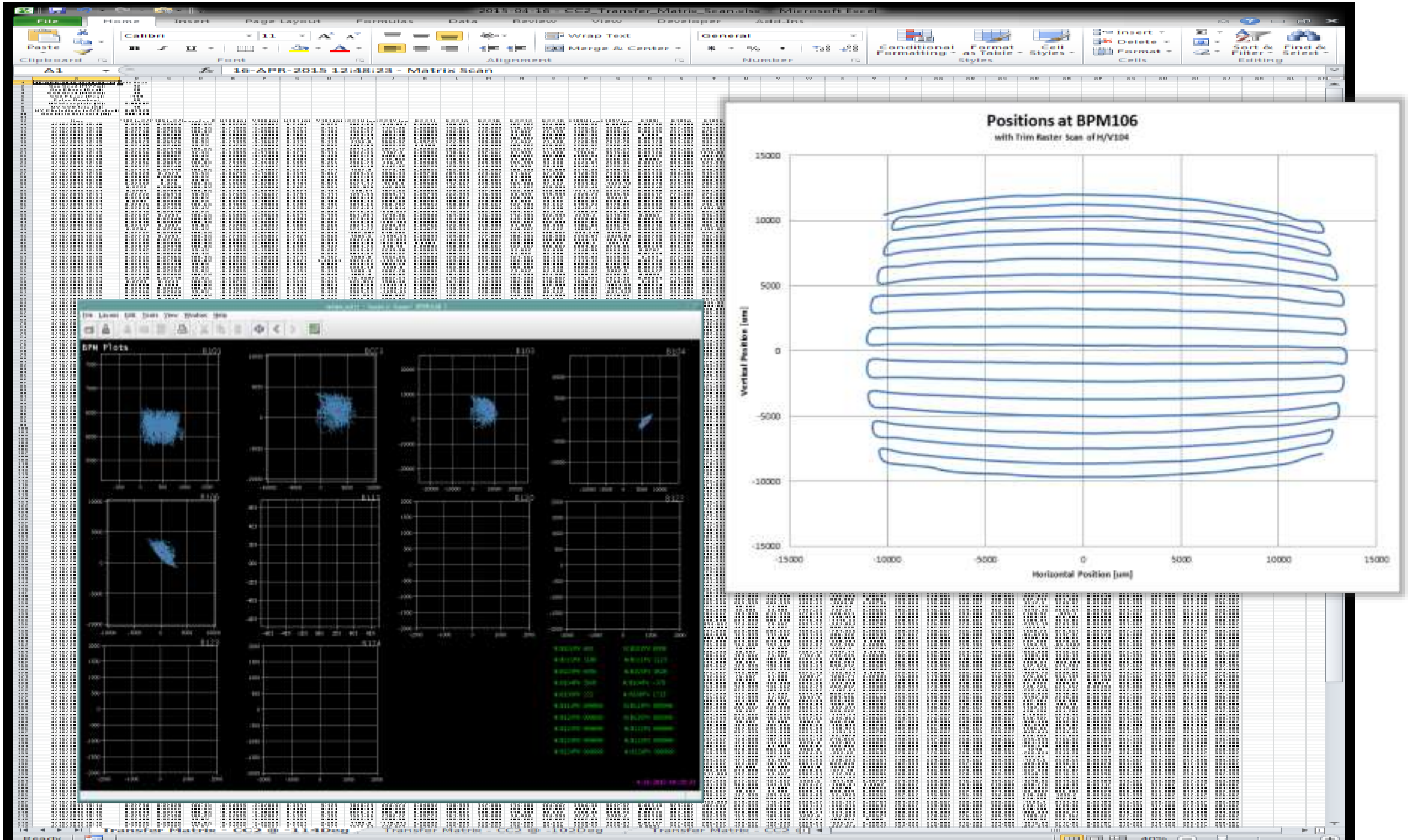
First Beam to Low Energy Absorber





Energy Measurement: Beam thru Dipole

Tesla cavity/CC2 ransfer matrix measurement



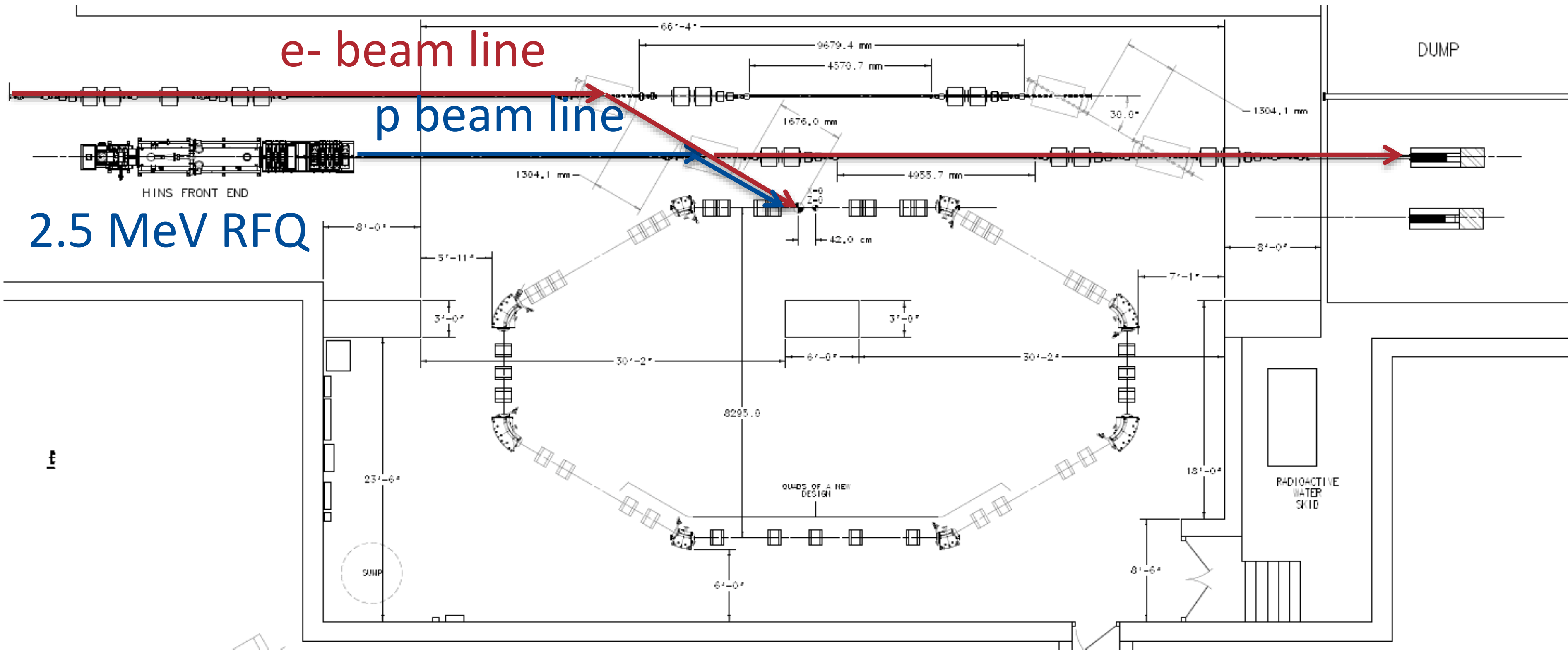
FY15 *e-* Injector Commissioning Activities

Extensive checkout list:

- Instrumentation
  - 9 BPMs, 2 Toroids, 1 WCM, Loss Monitors, Imaging Stations
- Machine protection system
- Machine stability and reproducibility
- Quad scan emittance measurements
- Beam based trajectory alignment
- Typical parameters:

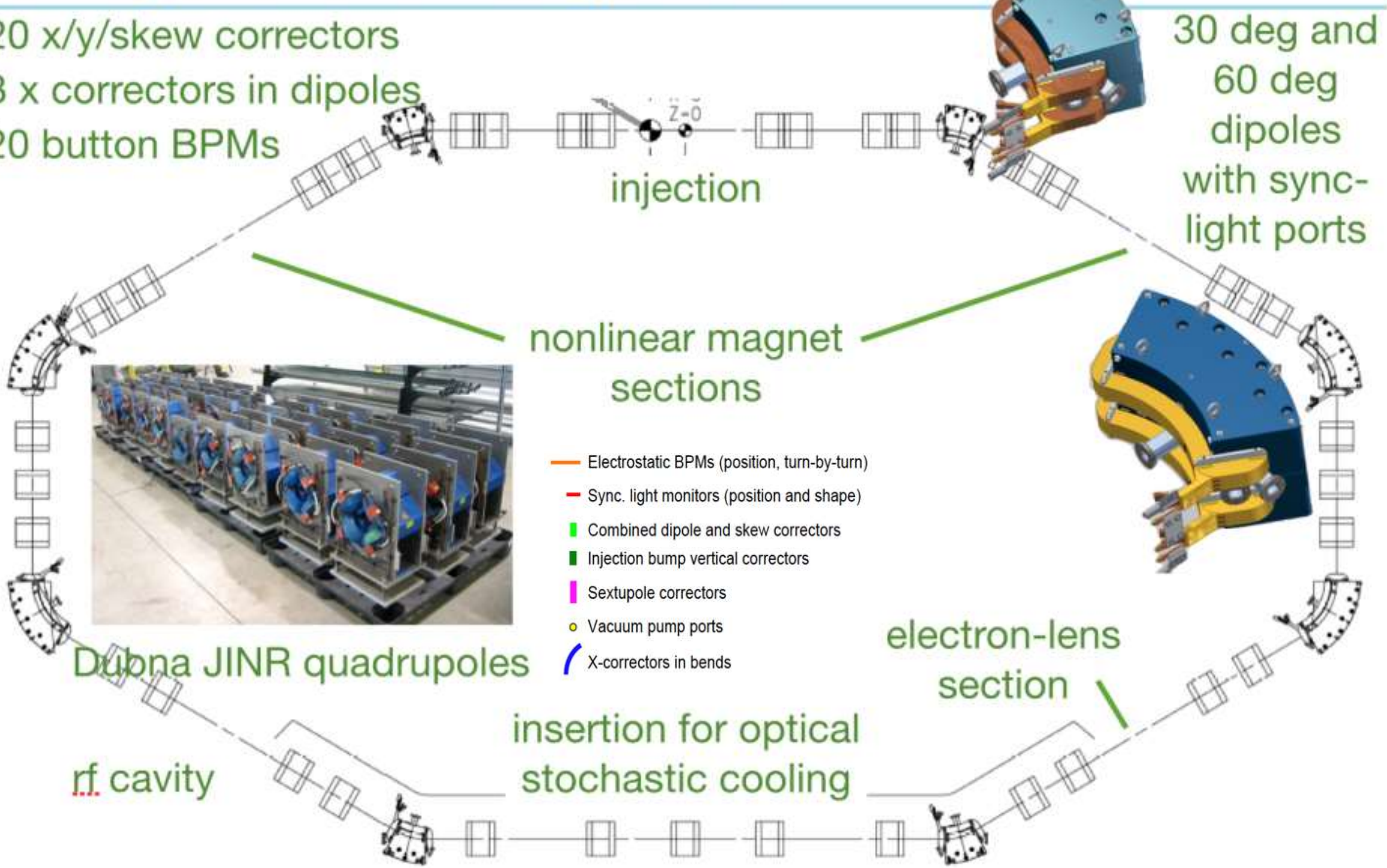
Bunch charge	0.25 nC
Gun gradient	42 MV/m
CC2 gradient	16 MV/m
Beam energy	20 MeV
Bunch length	6-8 ps (rms)

IOTA Ring



e- beam line
p beam line
2.5 MeV RFQ
HINS FRONT END
DUMP
66'-4"
9679.4 mm
4570.7 mm
1676.0 mm
1304.1 mm
4955.7 mm
30.0°
42.0 cm
8'-0"
5'-11"
3'-0"
30'-2"
6'-0"
30'-2"
7'-1"
8295.0
23'-6"
18'-0"
QUADS OF A NEW DESIGN
RADIOACTIVE WATER SKID
SUMP
6'-0"
8'-6"

IOTA layout and main components



IOTA Progress in FY15 (what's for FY16)

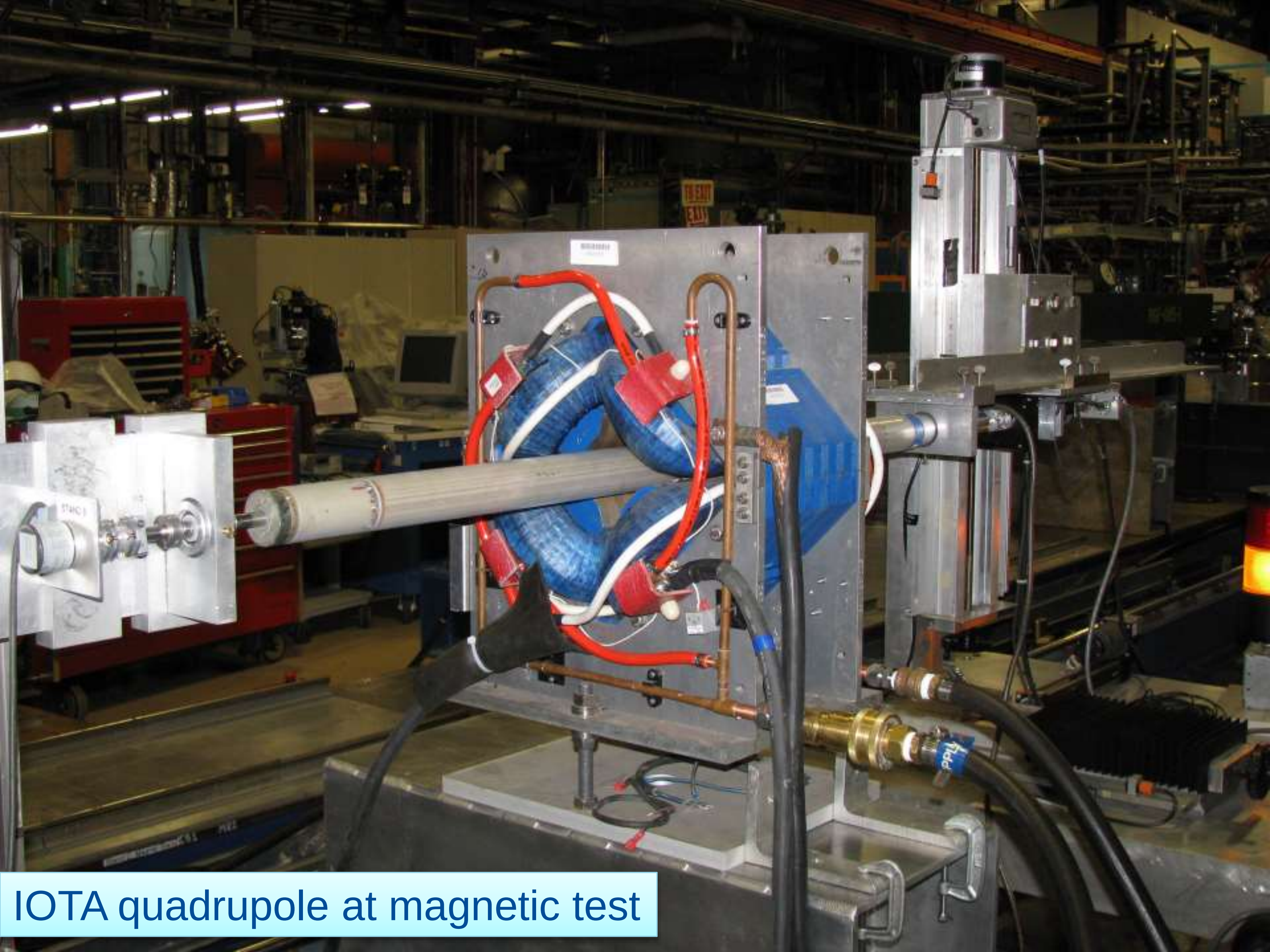
- Magnetic system:
  - Main dipoles manufacturing in progress, *first* magnet delivered Nov. 2015, the rest (9) to be delivered in 2016
  - 32 'Dubna' quadrupoles refurbished, performing magnetic measurements
  - 10 new quadrupoles ordered, to be delivered in March 2016
  - Corrector magnets (20) delivery Jan.-Feb. 2016
  - Power supplies purchased, installed. Cable pulls in progress.
- Vacuum system:
  - Dipole alum. chambers manufactured.
  - Vacuum pumps and gauges purchased.
- Mechanical:
  - Support stands designed, prototype in production.

IOTA Status

- RF system:
  - Old pbar cavity redesigned and refurbished/need RF generator
- Vacuum system:
  - Dipole alum. chambers manufactured.
  - 50% Vacuum pumps and gauges purchased/ 50% in FY16
- Injection system:
  - Kicker designed,parts procured, manufacturing in progress/ FY16
  - Pulse generator is reused from Tevatron, tested.
  - DC Lambertson design in progress / construction in FY16
- Instrumentation:
  - BPM bodies (21) manufactured, received; electronics procured.
  - Synchrotron light system (8) components procured / FY16-17

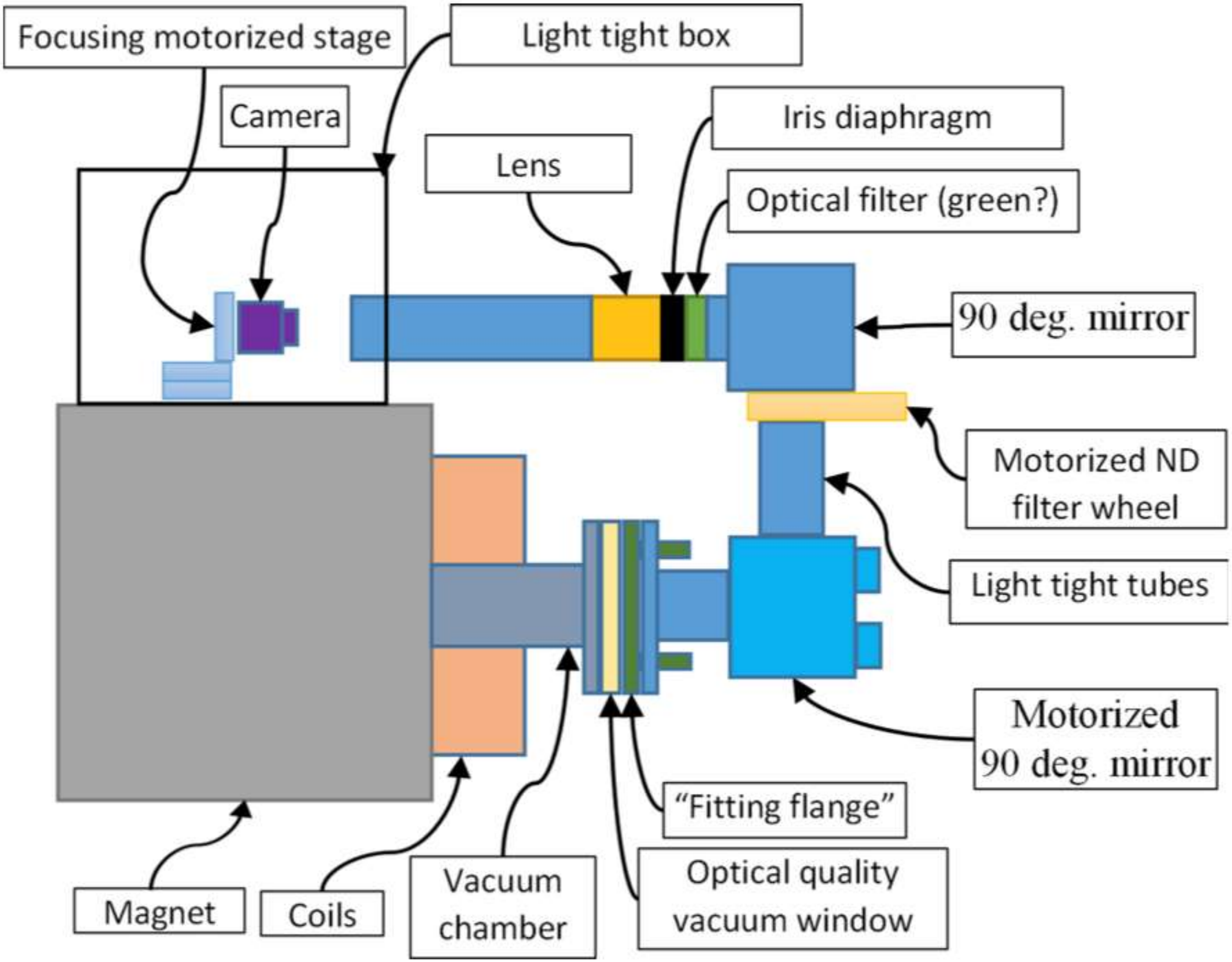

OLBS
IOTA 30-deg. dipole

IOTA ‘Dubna’ quadrupoles



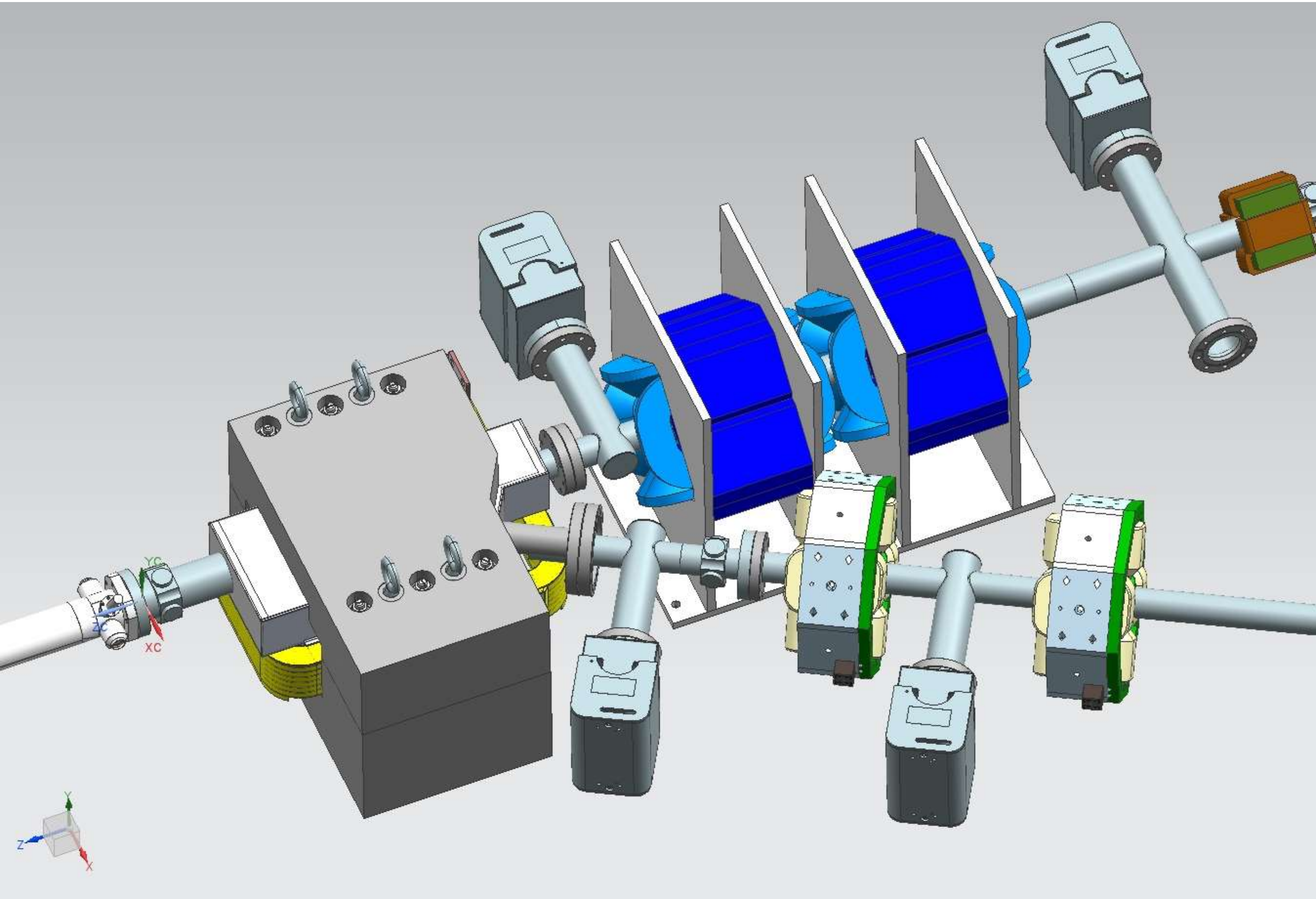
IOTA quadrupole at magnetic test

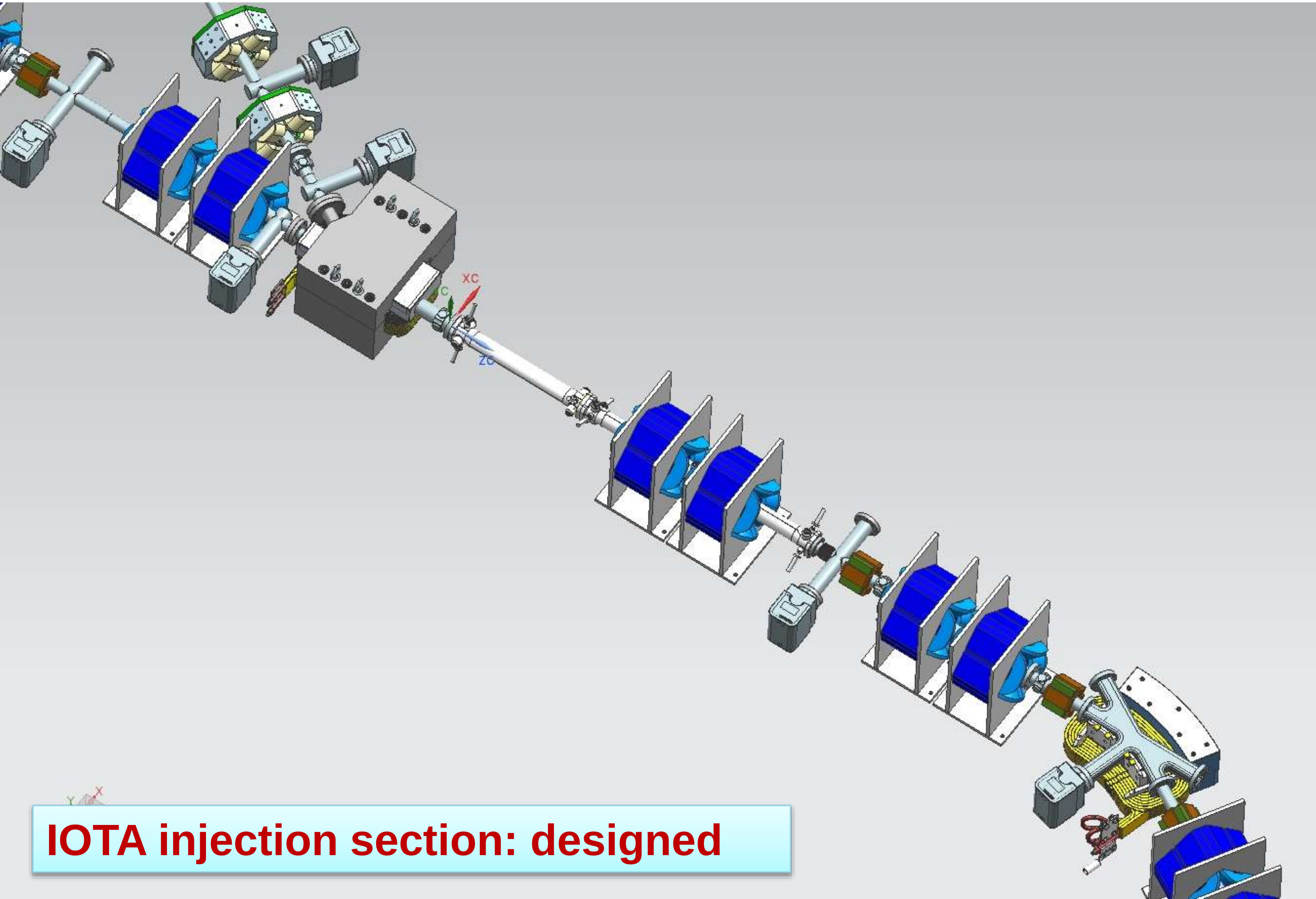
Pbar RF cavity refurbished for IOTA



IOTA Synchrotron Radiation Monitors (schematic)

IOTA injection Lambertson magnet: designed





IOTA injection section: designed

IOTA Staging – Phase II

After the IOTA commissioning with e-, we will move the existing 2.5 MeV (70 MeV/*c*) proton/H- RFQ to FAST to inject protons into the IOTA ring.

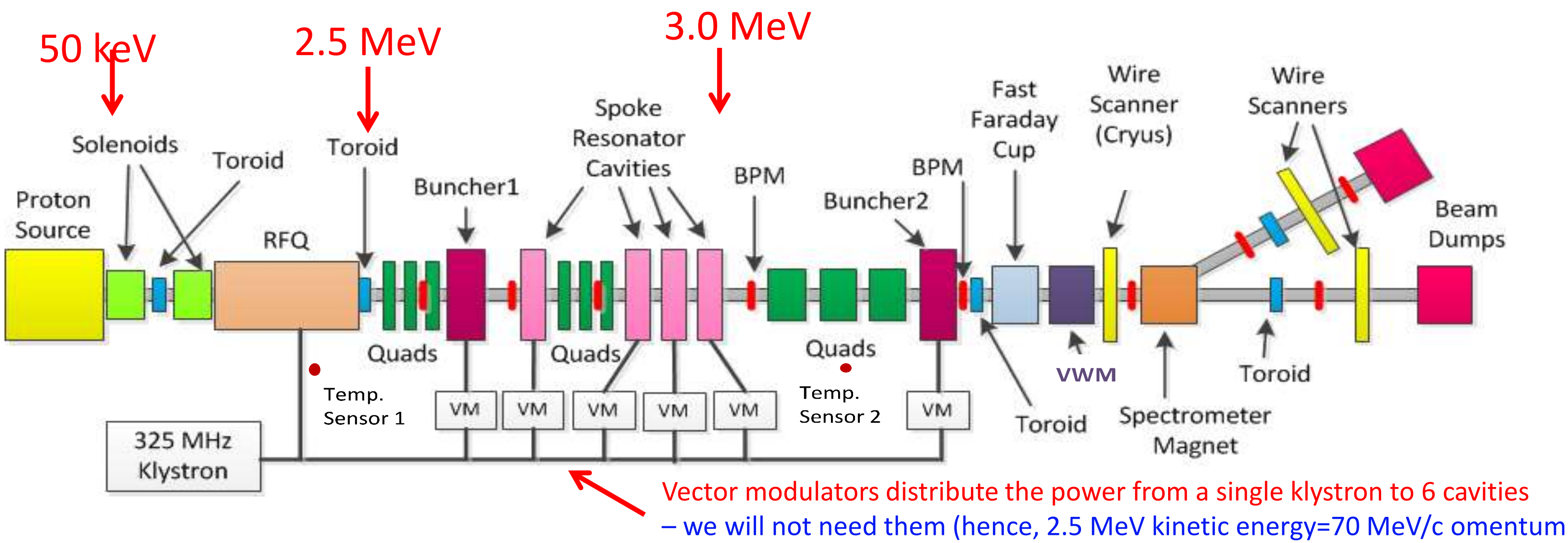
ΔQ_{SC} =0.5 for one-turn injection

*multi-turn injection possible

- Allows tests of Integrable Optics with protons and realistic space charge beam dynamics studies
- **Allows space charge compensation experiments**

IOTA Proton Injector

- To study high-intensity proton beam physics we need proton beam. Will use existing HINS 2.5MeV H- RFQ.
- The HINS ("High Intensity Neutrino Source") was developed as the front end of a pulsed "Project X" 8 GeV proton linac

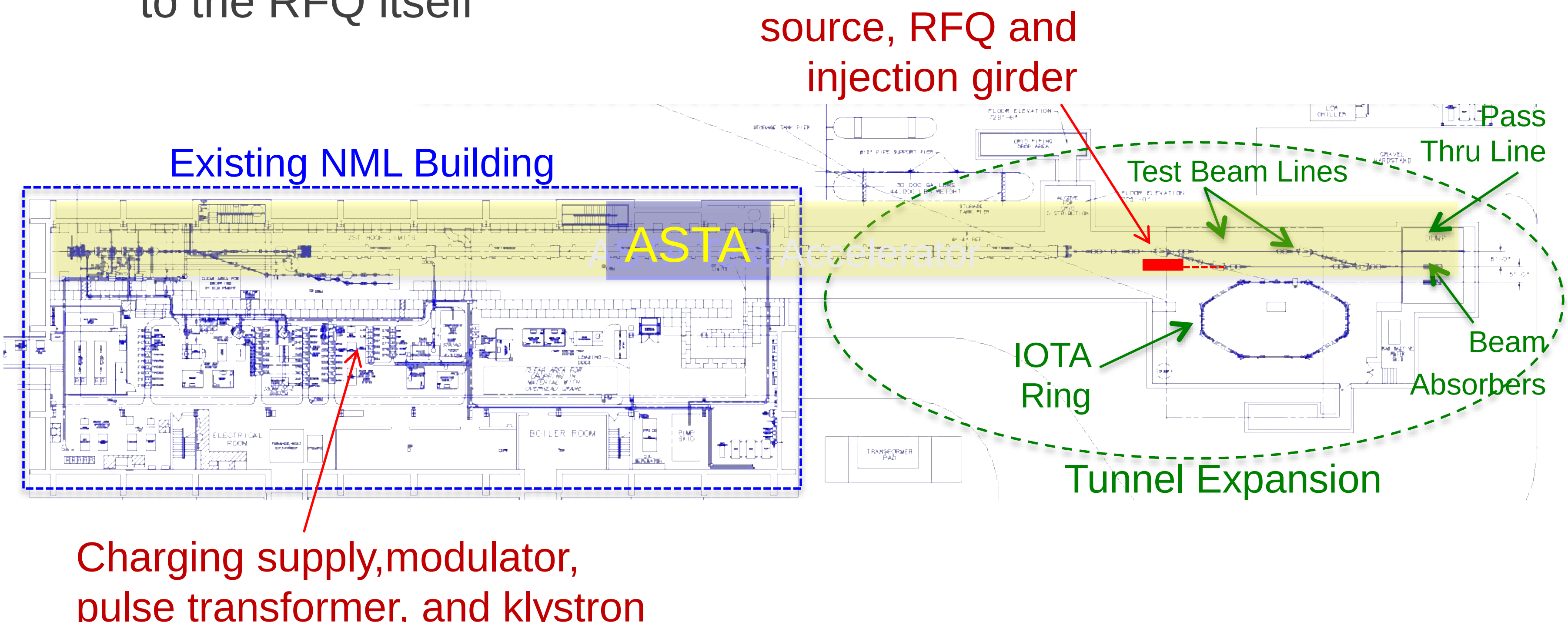


- Because of cooling problems, it never reached its design pulse rate
- Project-X (now PIP-II) specification was changed to a CW front end
  - HINS->PXIE
- HINS RFQ available for our use

FAST Proton Injector: Plan

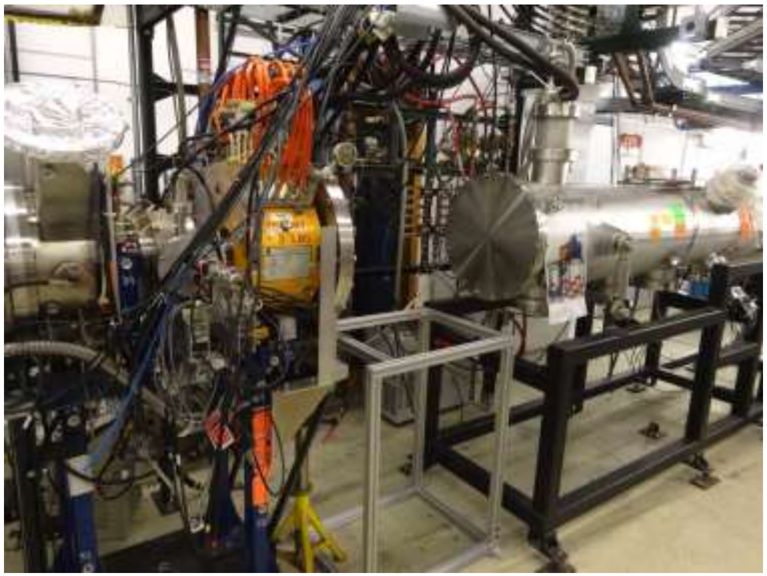
- Plan: resurrect HINS *in situ* at MDB (2016-2017)
- Completely characterize its performance (2017-2018 *)
- Once it works, move *everything* to FAST (2019 *)
  - Put all high power RF hardware in the upstream gallery and run coax to the RFQ itself

* 1 year sooner with modest extra funding



2015 Progress on IOTA Proton Injector

80 k$ supplemental (*thank you!)* has greatly helped to progress proton injector work:



- Ion source separated from RFQ in preparation for instrumentation.
- All parts requisitioned for refurbishment.
- On track to re-commission in January.

- Reconnected 325 MHz klystron to waveguide and coax.
- Continuing reconnection to RFQ.
- On track to deliver beam in spring of 2016.

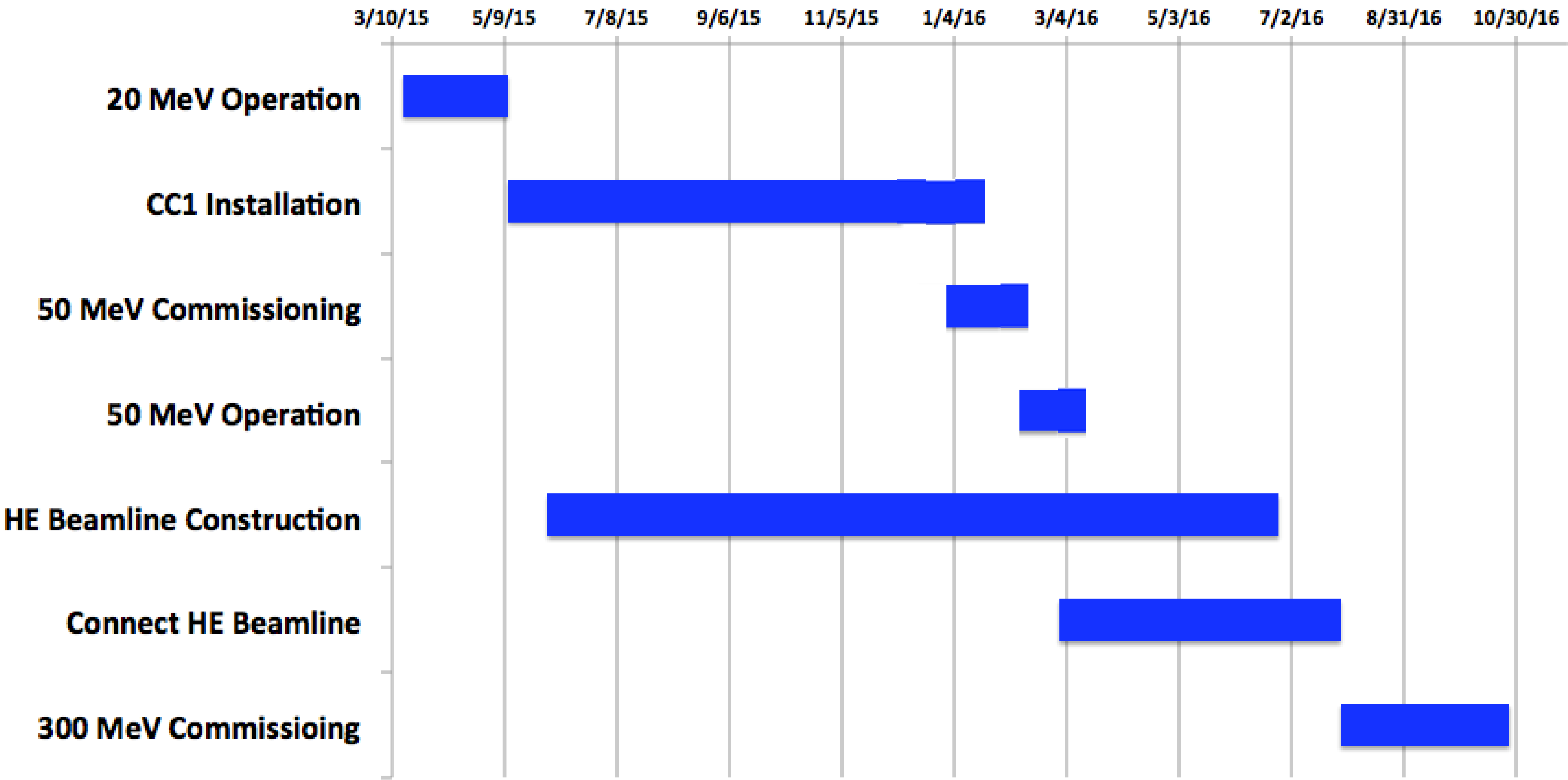
(3) FAST /IOTA in FY2016

FY16	50 MeV e- commissioned HE beam line 100% IOTA parts 80%

High Energy Beamline and Enclosure (FY16)

FAST Schedule in FY16

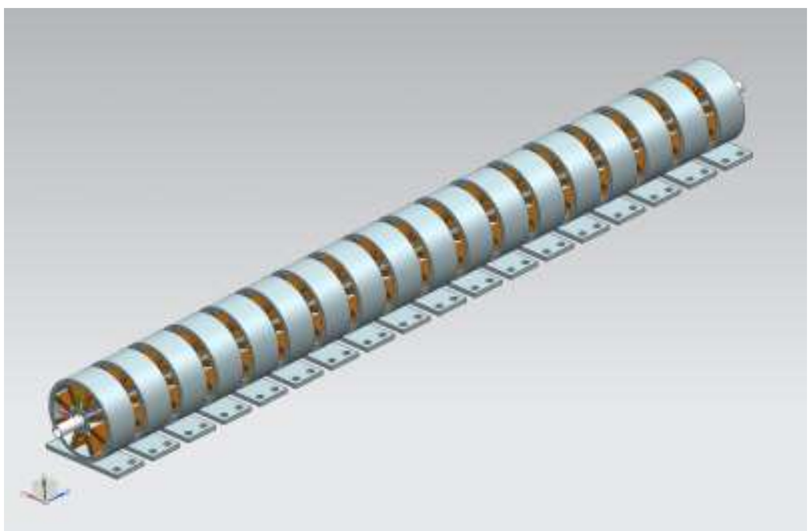
- Mostly determined by availability of mechanical, cryo and electrician labor (lab priorities)



Octupoles for IOTA Quasi-Integrable System

(in addition to many magnets to be built in FY16 already mentioned above)

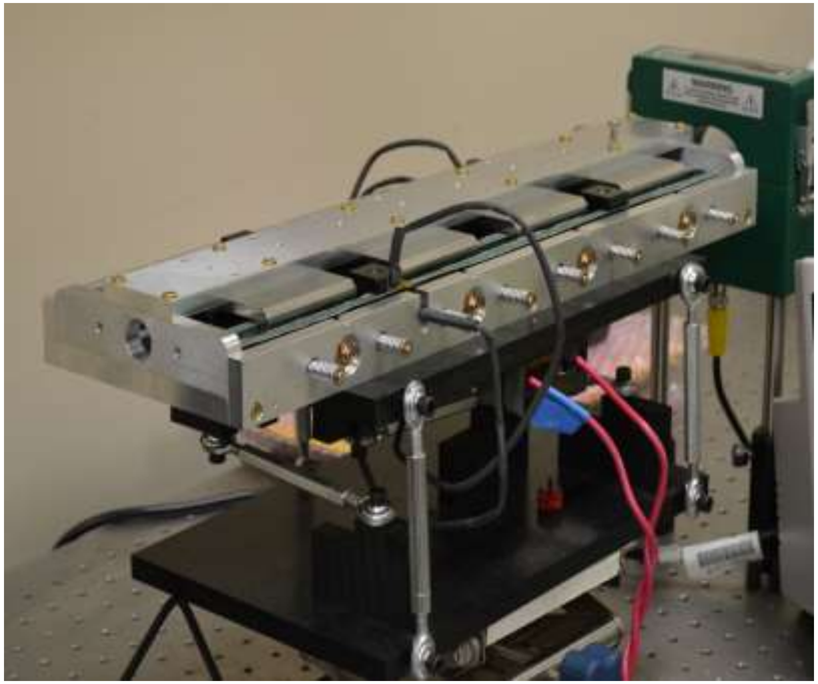
- 18 octupoles will be built
- all parts in hand except coils



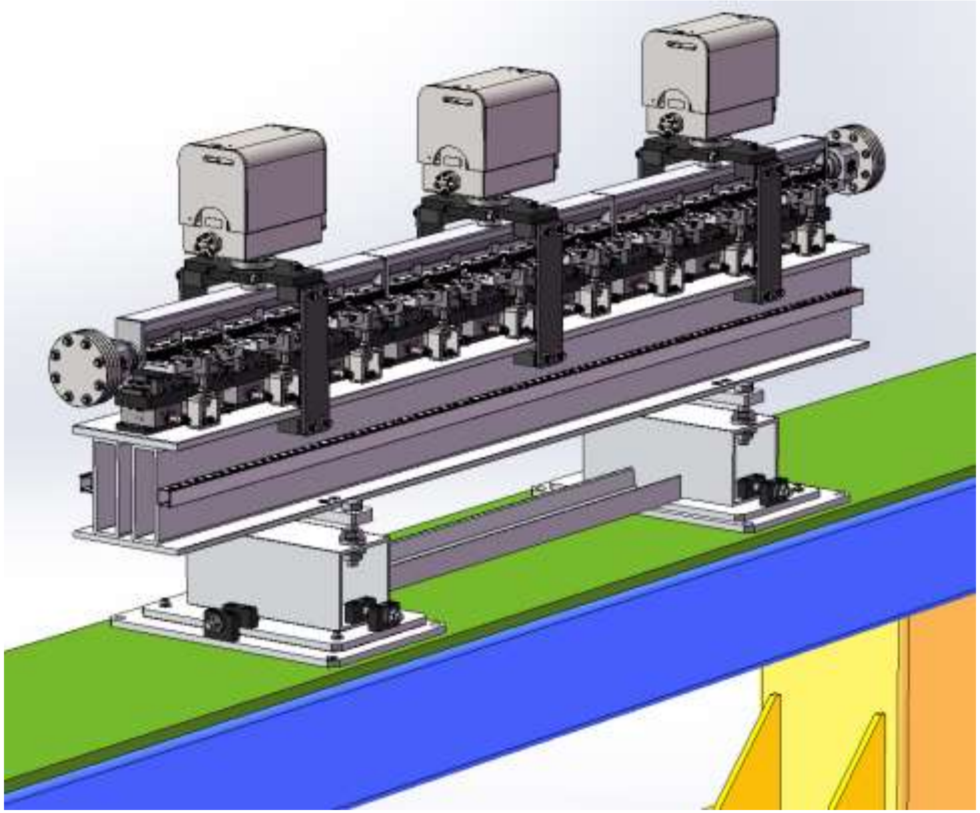
Summer engineering internship project

Nonlinear Magnet for Integrable IOTA

- Joint effort with RadiaBeam Technologies (Phase I and II SBIR)



Short prototype built in Phase I



1.8-m long magnet to be delivered in 2016

(4) FAST /IOTA in FY2017 and beyond, R&D, Collaborations

FY17	150 MeV CM2 to dump IOTA installed
FY18	IOTA *e-* commissioned IOTA research starts with *e-*
FY19	Proton RFQ move 50%
FY20	Proton RFQ move 100% Proton RFQ commissioned IOTA research starts with *p+*

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FY18	Proton RFQ moved 100% *p+* RFQ commissioned
FY19	IOTA research starts with *p+*
FY20	(IOTA research continues)

To Start IOTA p+ in FY19 : Add'l Resource Table

	FY16	FY17	FY18	M&S Loaded
TOTAL (w. OH)	$ 1,386,849	$ 925,983	$ 931,567	$ 3,244,398
IOTA e- Injector Infrastructure	518,910	-	-	$ 518,910
IOTA p Injector Infrastructure	266,003	400,895	406,480	$ 1,073,378
IOTA Ring Infrastructure	598,229	123,550	-	$ 721,779
IOTA Research Support	3,707	401,538	525,088	$ 930,332
Budgeted FY16-17 as of 06/15	**(895,375)**	**(730,375)**	**(730,375)**	
Additional Labor (1.0 FTE)	**200,000**	**200,000**	**200,000**	
Supplemental incl. 1FTE	**691,474**	**395,608**	**401,192**	**1,488,273**

* assuming FY17 as in FWP and FY18 same as FY17

IOTA Research: Beam Physics Drivers

1. **Nonlinear Integrable Optics** – Experimental demonstration of Non-linear Optics lattice in a practical accelerator
2. **Space Charge Compensation** – Suppression of SC-related effects in high intensity circular accelerators
   - Nonlinear Integrable Optics
   - Electron lenses
   - Electron columns
   - Circular betatron modes
3. **Beam collimation** – Technology development for hollow electron beam collimation

GARD

Collaborators

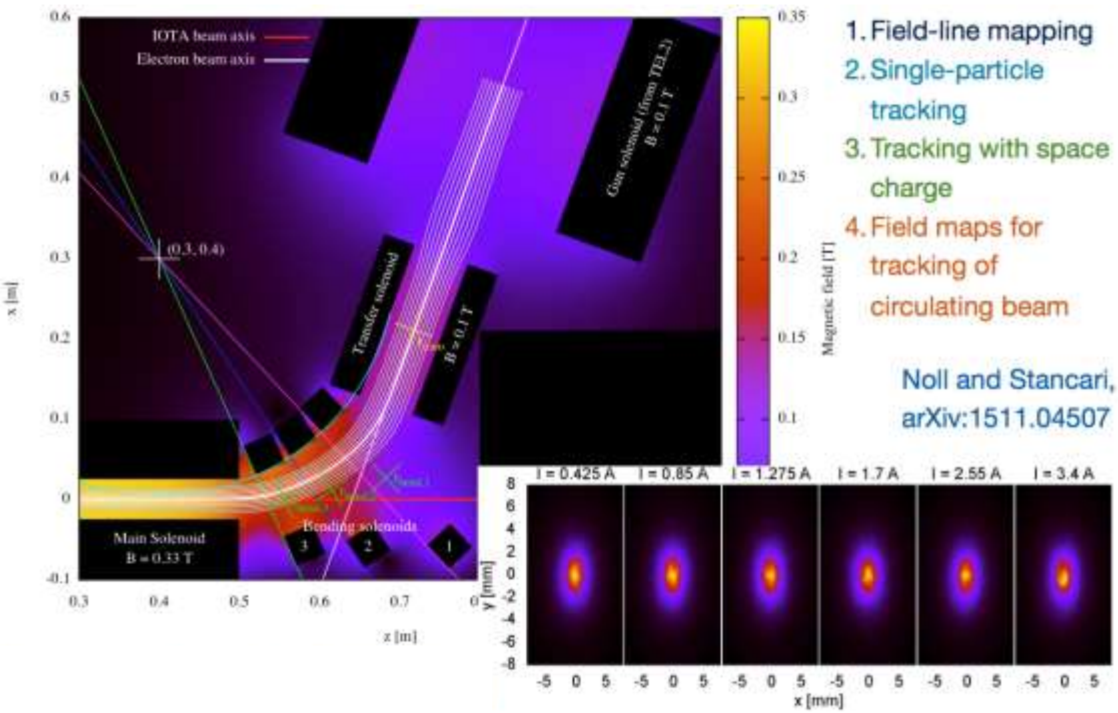
under discussion by collaborators:

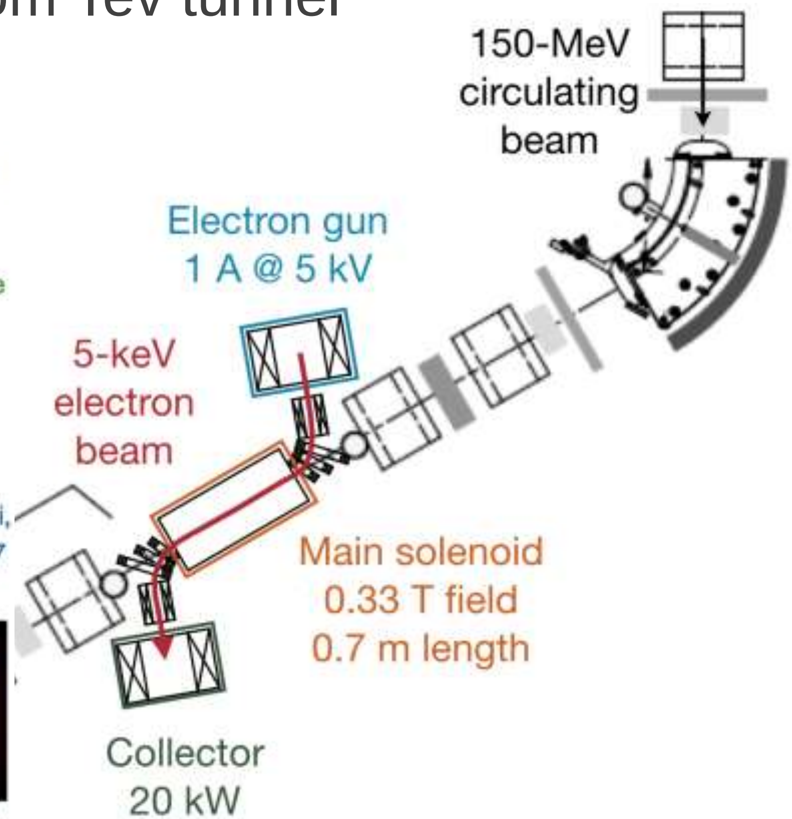
- **Optical Stochastic Cooling** – Proof-of-principle demonstration
- **Electron Cooling –** Advanced techniques
- **Laser-Plasma Accelerator –** Demonstration of injection into synchrotron
- **Quantum Physics –** Localization of single electron wave function

Collaborators

IOTA Electron Lens: Design Simulations

- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components:
  - Removed TEL-2 gun & collector from Tev tunnel
  - Refurbishment in progress





Scientific IOTA Collaboration Formed

- **22 Partners:**
  - ANL, Berkeley, BNL, BINP, CERN, Chicago, Colorado State, IAP Frankfurt, JINR, Kansas, LANL, LBNL, ORNL, Maryland, Michigan State, Northern Illinois, Oxford, RadiaBeam Technologies, RadiaSoft LLC, Tech-X, Tennessee, Vanderbilt

- **NIU-FNAL:** Joint Cluster of Research Excellence →

NIU/FNAL Joint Appointees:

Swapan Chattopadhyay

Philippe Piot

Bela Erdelyi

Young-Min Shin

Michael J. Syphers

FNAL Cluster members:

Sergei Nagaitsev

Vladimir Shiltsev

IOTA Science Workshop – April 2015

- By invitation only: 40 participants, 30 not from Fermilab
- ~25 presentations

Swapan Chattopadhyay
Workshop Chair

FOCUSED WORKSHOP ON SCIENTIFIC OPPORTUNITIES IN IOTA

https://indico.fnal.gov/conferenceDisplay.py?confId=10547

28-29 April 2015 *Wilson Hall*
US/Central timezone

* WP drafted

- Three Working Groups:

Nonlinear Dynamics (ND) and Space Charge (SC)

KISHEK, Rami (CHAIR)
SHILTSEV, Vladimir (CO-CHAIR)

Optical Stochastic Cooling (OSC) and Single Electron Quantum Optics (SEQO)

ZHOLENTS, Alexander (CHAIR, OSC)
KIM, Kwang-Je (CO-CHAIR, OSC and SEQO)
SHAFTAN, Timur (CO-CHAIR, SEQO)

Emittance Exchange (EE) , Radiation (R) and Laser-Beam Shaping (LBS)

WURTELE, Jonathan (CHAIR)
THANGARAJ, Jayakar (CO-CHAIR)

What Collaborators Bring to IOTA/FAST: Resources

Instrumentation/Diagnostics

- SBIR Phase II RadiaBeam Technologies
  - nonlinear magnet
- NIU (PI Chattopadhyay)
  - M&S $300k matching
- Fermilab LDRD (PI Chattopadhyay)
  - M&S $300k
- Submitted DOE GARD
  - UoC (PI Kim, Nagaitsev)
  - NIU (PI Chattopadhyay, Erdelyi)
  - LBNL (PI Mitchell)

Research

- NIU (PI Chattopadhyay) – OSC
  - 1 Postdoc + PhD student + M&S
- UoC "Innovations in Bright Beam Science"
  - 3-year NSF (PI Kim)
- NIU (DOE HEP, PI Piot) – OSC
  - PhD student + M&S
- NIU (DOE/DHS, PI Piot) – Υ-ray source
  - $1.94M over 5 years with RadiaBeam & FNAL
- Fermilab LDRD (PI Valishev) – IOTA->PIP-III
  - 1 Postdoc + PhD student
- SBIR Phase II RadiaSoft
  - space charge simulations

An Example of IOTA/FAST Collaboration

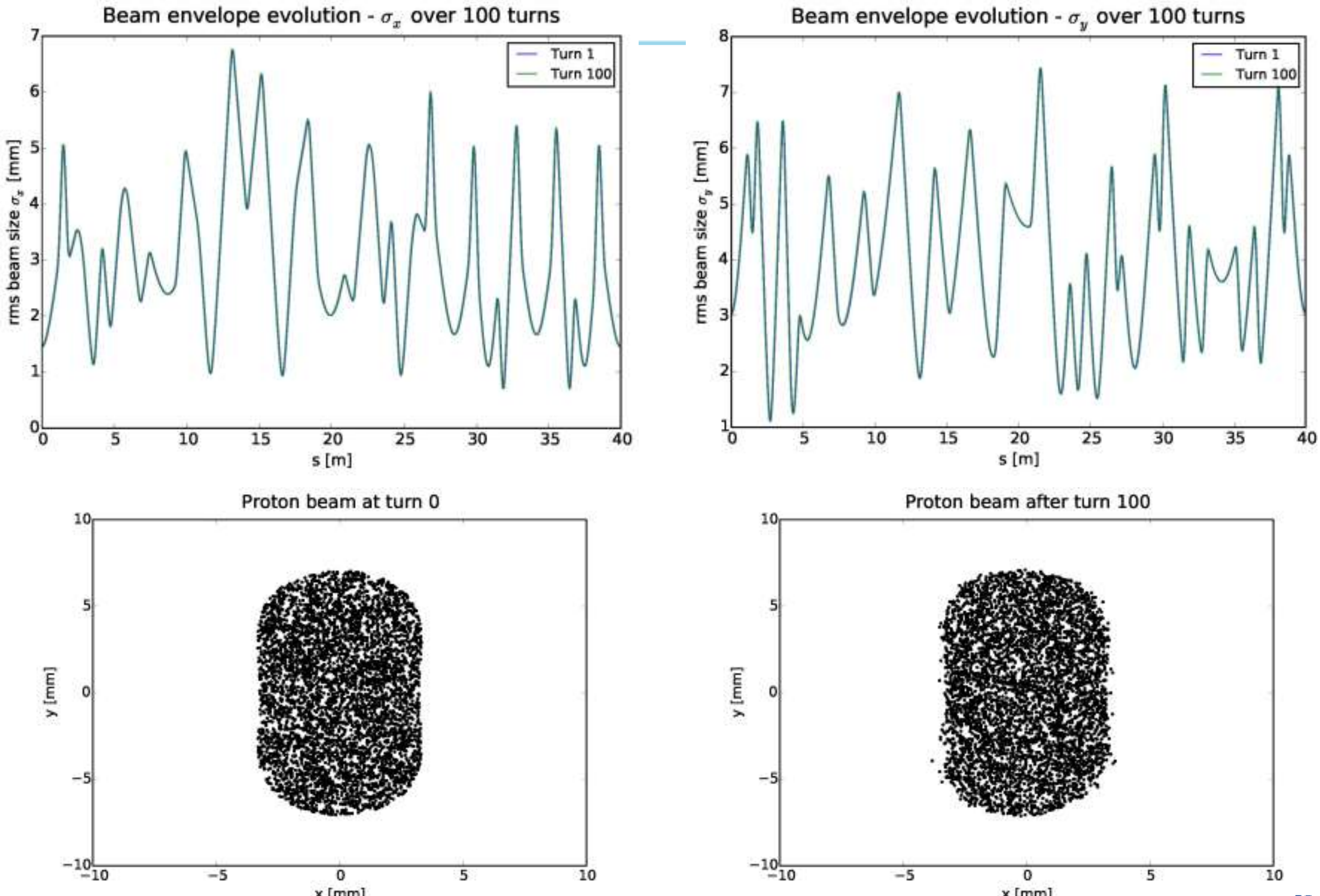
Simulations of Space Charge Effects on Beam Dynamics in the IOTA Ring

[&] radiasoft [#] Fermilab [ψ] University of Maryland

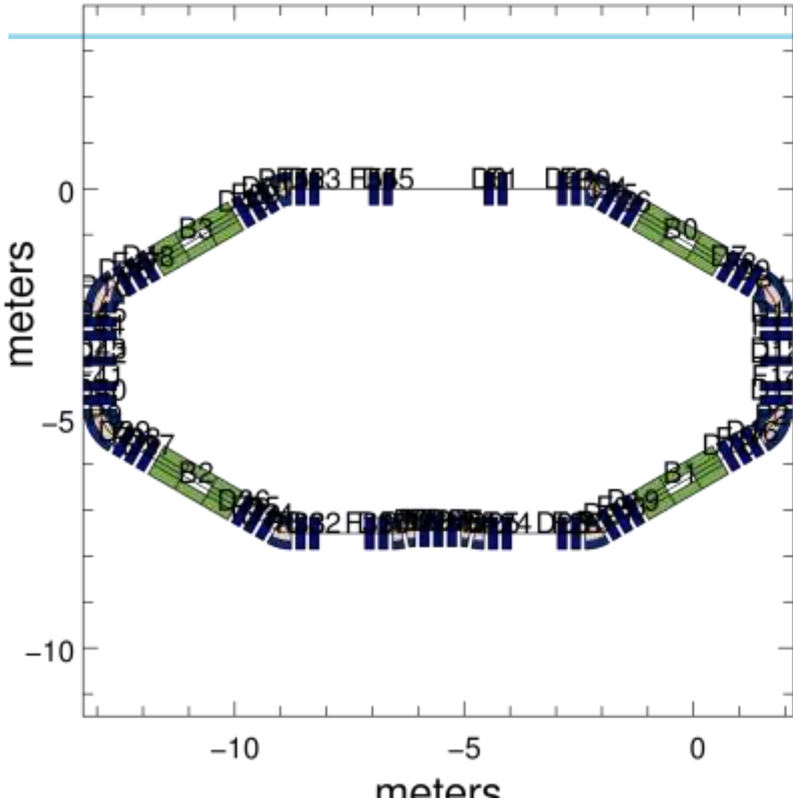
D.L. Bruhwiler[&] N. Cook[&] S. Webb[&] R. Kishek[&,ψ]

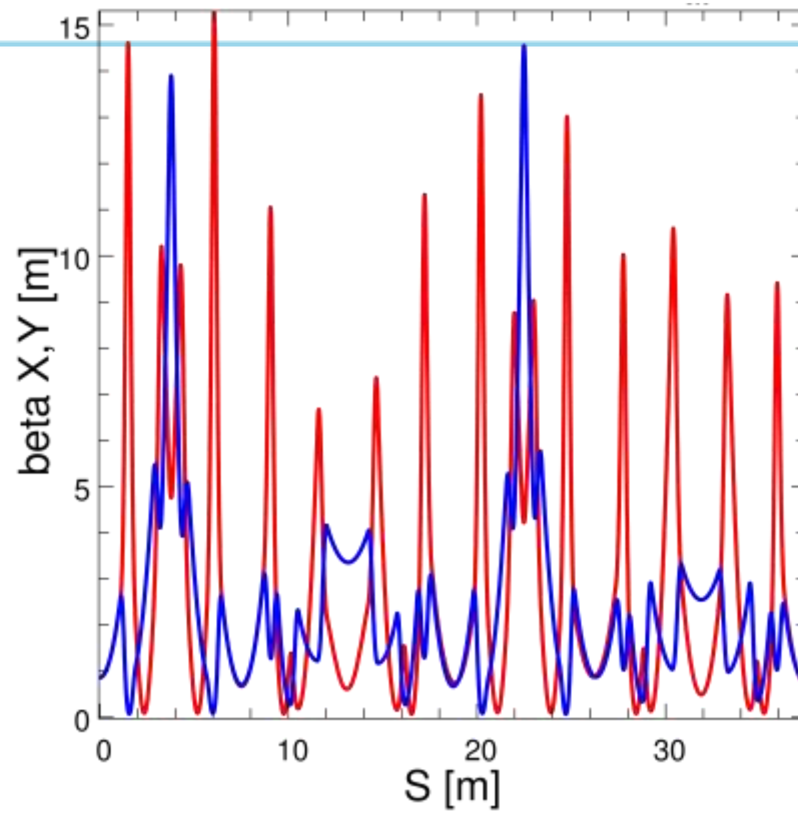
A. Valishev[#] E. Prebys[#] S. Nagaitsev[#]

SYNERGIA: 100 turns @ 14 mA – p+ beam is stable



WARP simulations of IOTA (ring)





- Looking at matching of underlying linear lattice @ 14 mA
  - must be well-behaved, to optimize nonlinear dynamics
- WARP can model injection from the RFQ in full detail
  - will require 3D mesh of the entire ring

Students at IOTA/FAST

2015 Graduates

Sriharsha Panuganti

PhD

NIU

Frederic Lemery

PhD

NIU

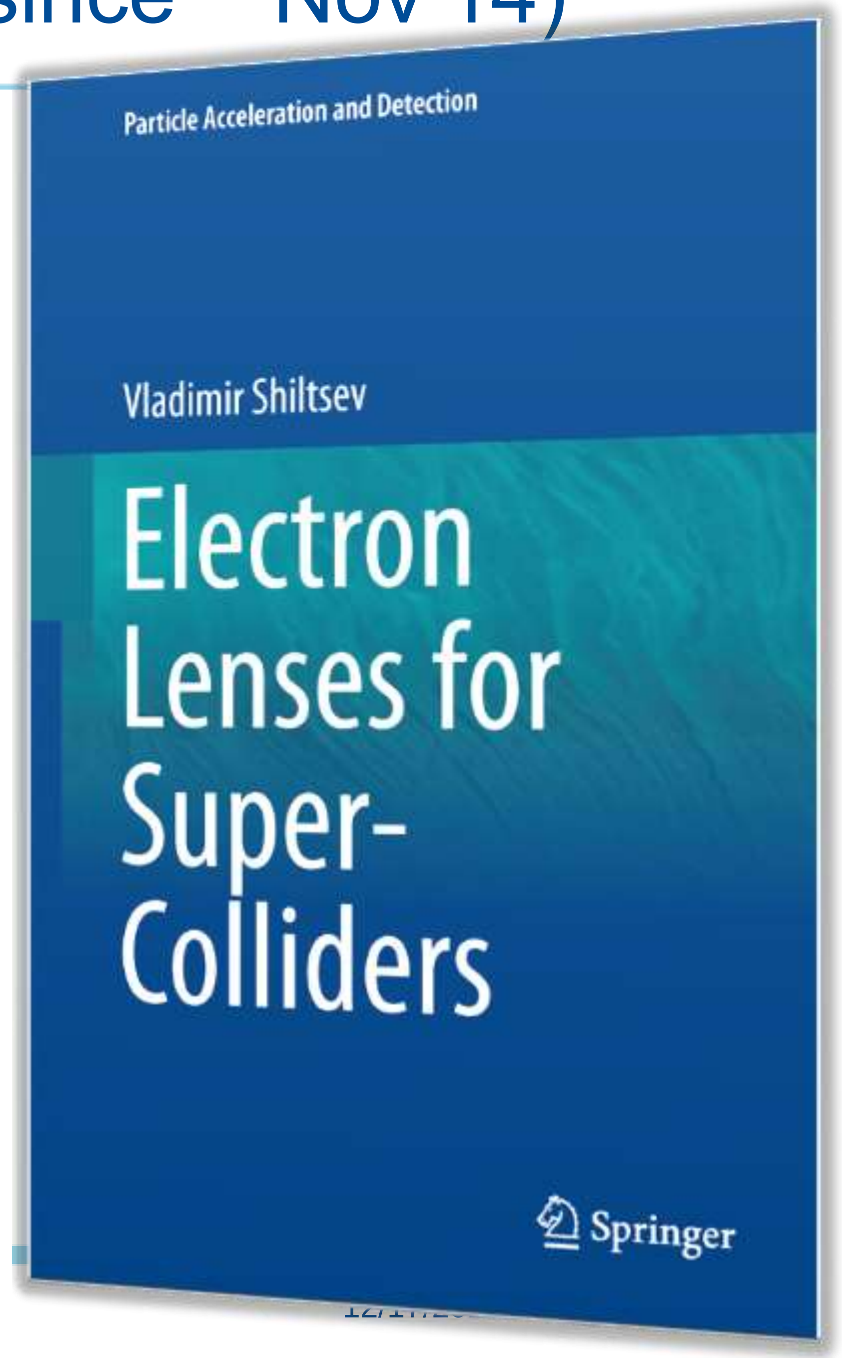
David P. Lopez

MSci

Universidad de Guantajuato (Mexico)

IOTA/FAST Publications (since ~ Nov’14)

- Peer-reviewed papers (5):
  - D.Noll,G.Stancari, arXiv:1511.04507 (2015)
  - S.Antipov, S.Nagaitsev, A.Valishev, arXiv:1502.01688 (2015) – *subm. for pub.*
  - F. Lemery P. Piot, PRSTAB 18, 081301 (2015)
  - D. Mihalcea, et al, APL107, 033502 (2015)
  - Y. M. Shin, et al, NIM-B 355, 94 (2015)
- Conference proceedings (12)
  - IPAC’15 – 9
  - Other - 3
- Misc. technical reports (21)
- Book on e-lenses
  - Chapter 5 on *Space-charge compensation with electron lenses*



Summary

- **IOTA/FAST construction continues, follows HEPAP Accelerator R&D Subpanel recommendations #2, #3**
  – GARD thrust: Accelerator and Beam Physics
- Impressive progress in FY15:
  – FAST electron injector began operations with 20MeV beams
  – CC2 transfer matrix and other measurements performed
  – About 50% of IOTA parts fabricated
  – (with supplemental support) *p*+ RFQ source refurbishment began
- Aggressive Plans/Expectations for FY2016:
  – Installation of CC1 will make 50MeV e- possible in early CY16
  – FAST plans for 150-300MeV e- beam in Q4 of 2016
    - <u>Subject to continued and timely engineering and mechanical support</u>

Summary – 2

- Plans for FY17 and beyond:
  - e- beam in IOTA FY17
  - 1st IOTA experiment on nonlinear integrable optics with e- is in good shape
    - Simulations done
    - Nonlinear magnets on track
  - p+ beam schedule depends on resources:
    - 2020 with flat/planned funding
    - 2018 with extra ~1.5 M$ *
      - ~1 FTE of EE and Mechanical Eng for 3 years and ~$900k M&S
    - Availability of engineering/mechanical labor may impact schedule
- Significant effort and resources are needed to establish experiments with protons:
  - Beam Profile Monitor; Loss Monitors; Scrapers; Reverse-injected pencil e- beam; Electron lens; Damper/anti-damper system;
  - (besides GARD funding) collaborators greatly help